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19. basilar membrane in determining the positioning of the spectrally dominant region for pitch perception. (4) A novel method for synthesizing single ripples of the classical rippled power spectrum of noise repetition pitch has been devised as a means to test theories concerning the bases for cophasic and antiphasic repetition pitch. (5) Illusory continuity of the fainter of two alternating sounds has been used by many laboratories to measure peripheral auditory response functions. These studies, employing pulsation threshold and auditory induction paradigms, have only examined changes in the fainter component, ignoring concurrent changes in the louder sound: Preliminary observations indicate that perceptual changes produced in the louder of the alternating sounds may be of comparable interest.

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MECHANISMS MEDIATING THE PERCEPTION OF COMPLEX ACOUSTIC PATTERNS

Richard M. Warren  
University of Wisconsin-Milwaukee  
Department of Psychology  
Milwaukee, Wisconsin 53201

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SUMMARY

Many sounds of ecological importance consist of complex acoustic patterns, and the research conducted during the previous grant has dealt with some of the rules and mechanisms governing the perception of such sounds. (1) Using randomly derived waveforms ("frozen noise" segments) as model long-period complex sounds, a series of experiments examined aspects of the stimuli used for recognition, and tested hypotheses concerning the basic principles governing the perception of these sounds. (2) New evidence was reported indicating that sequences of brief tones and brief vowels are perceived as global patterns or "temporal compounds". Different arrangements of component sounds form distinctive compounds, so that permuted orders can be discriminated without resolution into component elements. The same basic rules govern the perception of frozen noises, sequences of tones, and sequences of vowels, with overlays of special rules for melodic and phonetic sequences. (3) The pitches heard with triads of resolved and unresolved harmonics of odd-harmonic complex tones were examined to test a theory concerning the role of local complex temporal patterns on the basilar membrane in determining the positioning of the spectrally dominant region for pitch perception. (4) A novel method for synthesizing single ripples of the classical rippled power spectrum of noise repetition pitch has been devised as a means to test theories concerning the bases for cophasic and antiphasic repetition pitch. (5) Illusory continuity of the fainter of two alternating sounds has been used by many laboratories to measure peripheral auditory response functions. These studies, employing pulsation threshold and auditory induction paradigms, have only examined changes in the fainter component, ignoring concurrent changes in the louder sound: Preliminary observations indicate that perceptual changes produced in the louder of the alternating sounds may be of comparable interest.

## STATEMENT OF WORK

The goal of the research program supported by AFOSR has been to further our knowledge of mechanisms and principles governing the perception of complex sounds. The account which follows outlines the essential aspects of work which has been carried out, with more detailed treatment being furnished by the papers included as appendices.

1a. A study has examined the ability of listeners to identify random acoustic patterns (500 ms segments excised from Gaussian noise) following brief exposure. These patterns were heard first for about 30 s as recycling frozen noises. It was found that after hearing a frozen noise segment presented in this recycled (looped) format, listeners could identify the patterns after delays well beyond the limit of echoic memory, even when presentation of the patterns was changed from looped to linear format by opening the loops at arbitrarily selected positions. Thus, when a 500 ms frozen noise was first heard as a recycled pattern and then presented in linear form as a segment within a longer repeated frozen noise, listeners were able to tap in synchrony with that portion of the longer pattern corresponding to the previously heard segment. It appears that recycling can provide an efficient procedure for the rapid establishment of a stable memory for complex patterns (see Appendix 19).

1b. A study was undertaken to examine spectral factors involved in the ability of listeners to identify recycled frozen noise segments. The repetition frequencies employed were within the ranges described by Guttman & Julesz (1963) as "motorboating" (repetition periods from 50 to 250 ms) and "whooshing" (repetition periods from 250 ms to 1 s). These stimuli were presented first under one of three bandpass filtering conditions, and

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then presented broadband. A second experiment reversed the order of presentation, and required listeners to identify bandpass derivatives of previously heard broadband recycled frozen noises, without knowing in advance which of three frequency bands would be presented. The bands employed in both experiments were low (150-600 Hz), midrange (600-2400 Hz) or high (2.4 kHz - 9.6 kHz). For both presentation orders, recognition accuracy was good for the medium band and poor for the high-frequency band. For the low-range band, accuracy was good only when the isolated band was presented first. The salience of midrange frequencies is consistent with results for stationary profile analysis (Green, 1988; Green & Mason, 1985). Interestingly, if the bands were 1/3-octave (approximating the width of a critical band), accurate identification became impossible unless the matching stimulus had a similar bandwidth. It appears that flanking spectral regions of the broadband noise interacted with and changed the pattern within a critical band (see Appendix 18).

2. The ability to discriminate between different arrangements of components was compared for: (1) sequences of ten different sinusoidal tones; (2) pseudo-sequences of ten different frozen noise segments; and (3) sequences of ten different steady-state vowels (see Appendix 16). In the first part of the study it was found that when 40-ms tones were concatenated and recycled to produce a 400 ms pattern, minimal changes in order (interchanging the position of two contiguous tones) produced easily recognizable differences, even though the item durations were well below the 100 ms threshold for identifying the tones in extended sequences (Thomas and Fitzgibbons, 1971). In the second part of the study, segments of frozen noise were substituted for the ten 40-ms tones. When the noise segments were concatenated, they formed a single 400-ms frozen noise pattern. Repetition of this pattern produced the iterated "whooshing" described by Guttmann & Julesz (1963) for frozen noises repeated at this frequency (2.25 Hz). Although the

repeated frozen noise patterns were not composed of a succession of discrete acoustic elements as were the series of tonal items, listeners were able to discriminate between patterns produced by interchanging the position of two adjacent 40-ms segments with the same accuracy found for tonal sequences. It was concluded that the ability to discriminate between different arrangements of brief sounds in a sequence need not require resolution into an ordered series of components, but rather involves a global perception of the auditory patterns. A third part of the study dealt with the perception of sequences of ten 40-ms steady-state vowels. These vowel sequences were transformed perceptually into syllables and words. This "phonetic transformation effect" has been examined more fully in the studies described below in Section 3.

3. Sequences of steady-state vowels were found to have some rather interesting characteristics. When recycled sequences of three vowels were presented to listeners instructed to discriminate between the two possible arrangements, three distinct ranges were observed. Above 100 ms/vowel, the vowels could be named in their proper order in keeping with several previous studies (see Warren, 1982 for a review). At durations below 30 ms/vowel, the sequences did not resemble voice, but each of the two possible arrangements had a distinct timbre permitting different orders to be easily discriminated. However, from 30 through 100 ms/item, an interesting phenomenon was observed -- all listeners heard syllables and words, with different arrangements of the same vowels producing different words (for example, with the vowels corresponding to those in "hud," "had," and "heed," a listener reported hearing "kettle" with one order and "puddle" with the other). When sequences of ten 40-ms vowels were used, different arrangements produced different illusory syllables and words. When nonsense syllables were reported, they always followed the rules governing the clustering of phonemes in English. As with the ten-item tonal sequences described in Section 2 above, minimal changes in order

(interchanging the position of two contiguous vowels) produced different illusory verbal forms. Another curious feature of the perception of vowel sequences was that listeners usually heard two simultaneous verbal forms with different timbres -- one corresponding to high spectral components and one to low spectral components, with a dividing frequency usually occurring at about 1500 Hz. Three papers dealing with this phenomenon are included as Appendices -- one published paper (**Appendix 8**), one in press (**Appendix 11**), and one submitted for publication (**Appendix 14**), so that further details need not be given here. It should be noted that the individual vowels in the sequences giving rise to illusory words can be identified readily when presented in isolation -- it is only when presented in sequences that their identity is lost and a new verbal "temporal compound" is formed.

The observations made with vowel sequences are consistent with the hypothesis that speech perception has evolved from an ability to perceive auditory patterns holistically (an ability shared with nonhuman mammals), with an overlay of special linguistic rules applied to these vocal patterns (**Appendix 1**).

4. Recognition of sequences of brief sounds requires not only that the patterns have the same components in the same order (as demonstrated in Sections 4 and 5 above) but, as shown by Sorkin (1987), Sorkin & Montgomery (1991), and Warren (1974), they also must have similar item durations. Application of this principle to music leads to the prediction that a "temporal template" for melodic recognition will not only have a lower limit of note durations, but also an upper limit, so that melodies played too slowly should become unrecognizable. Using a pool of melodies familiar to listeners when played at normal tempos, both upper and lower limits for melodic recognition were determined for listeners without special musical training. When presented in a recycling mode, with the initial

note near the middle of the melodic phrase, the durational range permitting recognition approximated that reported by Fraisse (1963) as the duration of notes customarily used for melodies (approximately 150 ms to 900 ms). Below this range, the rapid sequence of notes produced distinctive patterns which were recognizable, but not as melodies. Above this range, the slow succession of notes was unrecognizable to subjects without musical training, but a group of musicians could recognize the melodies by employing their skills of musical notation for encoding the tunes (Appendix 9).

5. It is generally accepted that the pitch of a complex tone is largely determined by a "dominant" spectral region in the vicinity of the fourth to sixth harmonics. One possible reason for this positioning of the dominant region was first expressed by Zwicker & Feldtkeller (1967) who considered that the separation of adjacent harmonics is adequate to permit the spectral resolution of components, while at the same time the spacing is close enough so that several harmonics can interact within a single critical band to produce iterated complex temporal patterns on the basilar membrane. Dr. James Bashford and I reasoned that if we used an odd-harmonic sequence (1st, 3rd, 5th, ...) the spacing of harmonics would be doubled, and the dominant region should be shifted to the vicinity of the 9th and 11th harmonics. Another desirable consequence of using odd-harmonic sequences is that the complex temporal pattern (produced when several of the upper harmonics fall within a critical band) results in a pair of pseudoperiods and corresponding pitches -- one of these pitches is a little more and the other a little less than an octave above that of the fundamental (or ensemble waveform repetition frequency). When an all-harmonic complex tone is used, it is difficult to separate the pitches attributable to resolved harmonics from pitches attributable to harmonic interactions, since their values are each equivalent to that of the spectral fundamental. In our experiment, we used triads of successive odd-harmonics. As can be seen in Figure 1, the lower harmonic triads

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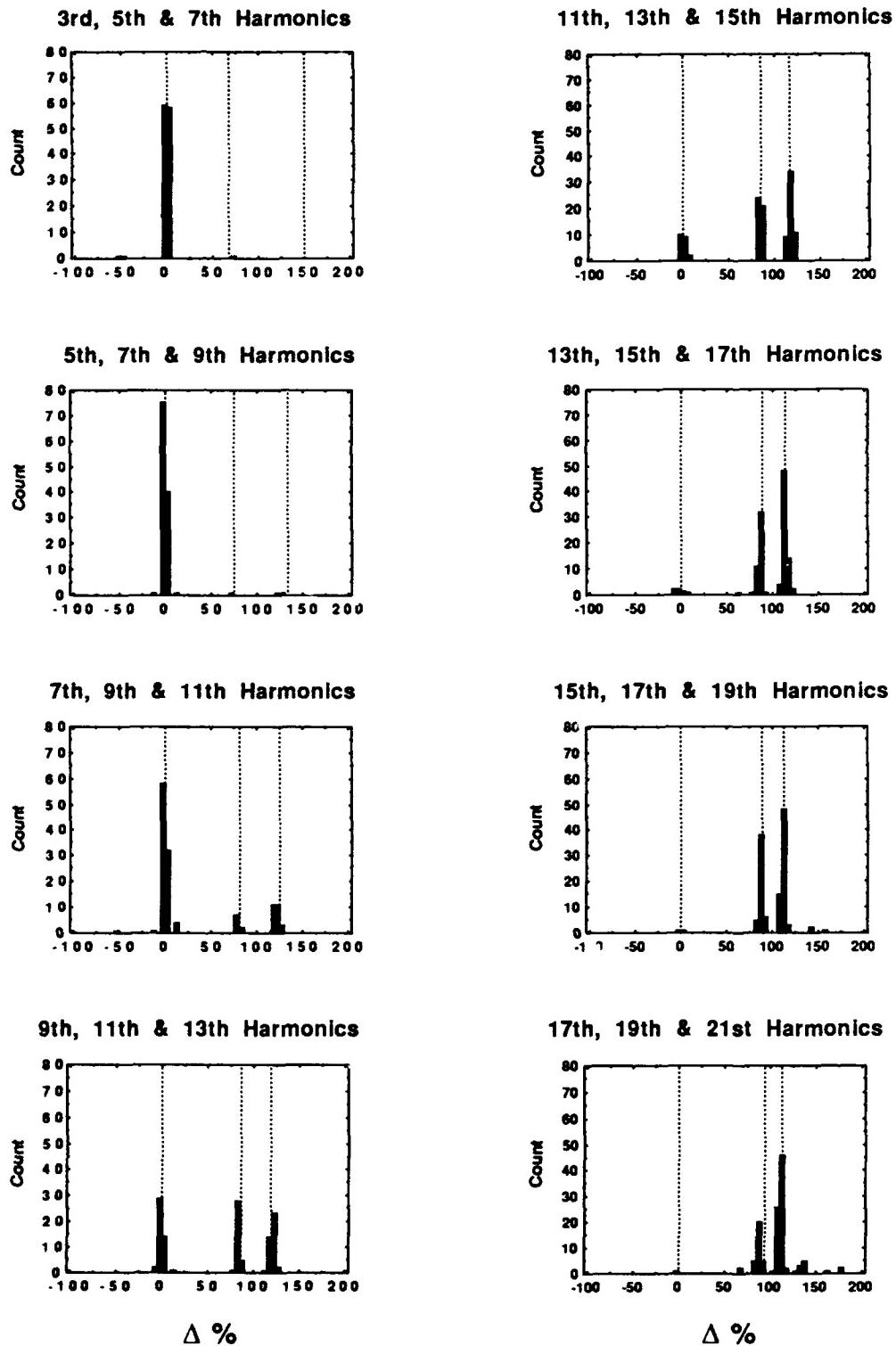


Fig. 1. Histograms of low-pitch matches (expressed in  $\Delta\%$  relative to the fundamental) for consecutive odd-harmonic triads. Results for each triad are based on 120 matches to the dominant pitch, summed across four listeners and five fundamental frequencies ranging from 100 Hz to 200 Hz. The dashed vertical lines represent exact matches to the fundamental frequency ( $1/t$  Hz) and to the two waveform pseudoperiodicities  $[2 / (t \pm 1/t)]$  Hz, where  $t$  is the frequency of the center harmonic of the triad.

gave rise to a pitch corresponding to the fundamental of the harmonic series, while the upper harmonics gave dual pitches matching the pseudoperiodicities of the waveform. Thus, harmonics within the putative range of spectral dominance gave rise to all three pitches -- the fundamental, and the pair of higher pitches in agreement with theory (see Appendix 24).

6. Mixing a broadband noise with itself following a delay of  $t$  s produces a series of ripples in the power spectrum. The peaks of these ripples occur at integral multiples of  $1/t$  Hz and a pitch can be heard corresponding to that of a sinusoidal tone of  $1/t$  Hz for delays ranging from about  $5 \times 10^{-4}$  s (corresponding to 2 kHz) through  $2 \times 10^{-2}$  s (corresponding to 50 Hz) [Fourcin, 1965; Bilsen, 1966; Wilson, 1966]. This "repetition pitch" has characteristics of continuing interest for theories of pitch perception.

Warren & Bashford (1988) proposed a theory concerning the basis for repetition pitch (RP), supporting their theory with data derived from filtered cos- RP (noise added to itself with a delay  $t$  and polarity inversion) (see Appendix 2). This theory considers that broadband RP results from a weighted averaging of pitches from different spectral regions. For a 1/3-octave band (approximating a critical band) with a center frequency of  $f$  Hz, an additional delay of  $\pm 1/2 f$  s is produced by polarity inversion, so that cos- RP based upon local delay (repetition time) becomes  $[1/(t \pm 1/2 f)]$ . Pitches were determined for cos- RP based upon broadband, bandpass, band-reject, high-pass and low-pass conditions for various values of  $t$ . The results obtained supported the weighted pitch averaging theory. However, this conclusion was questioned by Bilsen (1990) who continued to maintain that broadband cos- RP resulted from a pseudofundamental calculation based upon peaks occurring in the spectrally dominant region.

We have recently prepared stimuli which may help resolve this controversy, as well as answering additional questions concerning the bases for repetition pitch. By synthesizing separate noisebands with rectangular spectral profiles (i.e., infinite slopes at cut-off frequencies) it is possible to create single ripples by mixing the noiseband with itself following an appropriate delay. Sixteen consecutive ripples with bandwidths of 200 Hz ( $t = 5$  ms) have been synthesized with peaks at 200, 400, 600,... 3200 Hz, and corresponding bandwidths of 100-300, 300-500, 500-700, ... 3100-3300 Hz. Each band consists of 2000 successive harmonics of 0.1 Hz, with each harmonic having the same amplitude and a separate randomly determined phase, effectively producing a frozen noise with a repetition frequency of 10 s. The individual bands were then recorded on separate tracks of the 16-track recorder, so that the 16 ripples could be played back through a 16-channel mixer singly or in any desired combination. The value of  $1/t$  Hz (which determines bandwidth, center frequencies, and frequency separation of the consecutive peaks in a broadband rippled power spectrum) can be adjusted from the nominal value of 200 Hz to any desired value from 100 to 400 Hz by controlling the playback speed of the recorder. Preliminary experiments with this stimulus have already indicated that (contrary to some suggestions in the literature) no single ripple can produce repetition pitch. Preliminary observations also indicate that removal of the even-numbered spectral mountains from a normal cos+ rippled power spectrum produce a pitch equivalent to that of an antiphasic (cos-) rippled power spectrum with the same interpeak spacing, in apparent conflict with autocorrelational theories for repetition pitch. It is planned to use this novel pitch stimulus in a variety of other ways.

7. The illusory continuity of signals interrupted by a louder sound of appropriate spectral characteristics has been studied intensively since the 1970's. One line of investigation, involving dozens of published papers, started with Houtgast's (1972) introduction of the

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"pulsation threshold" procedure, in which listeners determine the maximum intensity of a fainter sound (usually a sinusoidal tone) permitting the illusion of continuity when alternated with a louder sound having an appropriate amplitude spectrum. The major goal of pulsation threshold studies has been to obtain psychophysical measures of peripheral neural mechanisms, cochlear mechanics, and lateral suppression. Another line of investigation (with considerable overlap with the pulsation threshold paradigm) was based on auditory induction theory (Warren, Obusek, & Ackroff (1972). Warren has considered that there were three basic types of illusory continuity: (1) "homophonic continuity" involving the illusory continuity of the fainter of two alternating levels of the same sound; (2) "heterophonic continuity" in which the louder inducer and the apparently continuous inducee are different sounds (as in pulsation threshold studies); and (3) "contextual catenation" in which the inducer causes perceptual synthesis of a contextually appropriate sound differing from preceding and following segments of the interrupted inducee, as in the "phonemic restoration" of segments of speech replaced by louder extraneous sounds of appropriate spectral characteristics. (For detailed review of the history of experiments on illusory continuity and some theories concerning its basis, see Warren, 1984).

All of these earlier studies examined the continuity of the fainter sound, with virtually no attention being paid to changes that might be occurring in the louder sound. However, Warren et al. (1972) and Houtgast (1972) have suggested that illusory continuity is the reversal of masking. This suggests that some of the neural input generated by the louder sound may be subtracted and used for the perceptual synthesis of the missing fainter sound. In opposition to this view, Bregman (1990) has suggested that the inducer (at least for phonemic restorations) undergoes no perceptual change of its own, but acts as a catalyst or trigger for restoration via a Gestalt-like closure.

Observations made very recently (in the last few months) have indicated that the residue has some interesting and hitherto unexpected properties. When Dr. Bashford and I examined the effect of alternating two levels of sinusoidal tones, we obtained the results shown in Figure 2 for a 70 dB sinusoidal tone alternated with another sinusoidal tone at 68 dB. Despite the lack of induction over much of the frequency range of the fainter tone, matching to the apparent intensity of the pulsed inducer demonstrated a subtractive phenomenon which reduced the apparent intensity of that sound. The homophonic condition (alternating 68 and 70 dB SPL levels of a 1000 Hz tone) produced some very curious (and interesting) effects. Homophonic continuity resulted in a dramatic change in the quality of the 70 dB inducing tone. Apparently, subtracting the neural input corresponding to the 68 dB level left a residue unlike any sound listeners had heard before. The

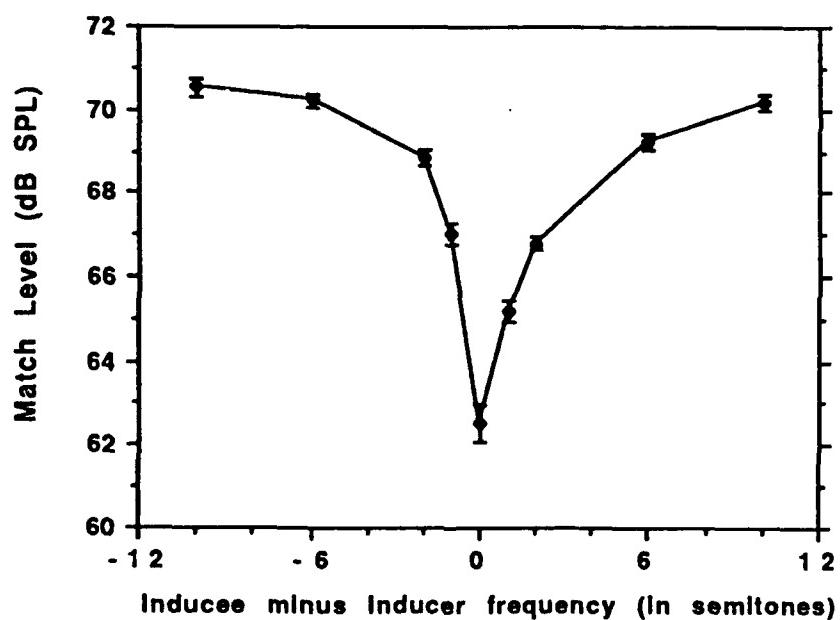


Fig. 2. The average loudness match for a 1 kHz inducer, plotted as a function of the inducee frequency. The 70 dB inducer and the 68 dB inducee were both pure tones, presented alternately at a rate of 2.5 Hz (200 ms on/off). Data represent the results for two listeners who provided a total of 80 judgments at each inducee frequency.

novel nature of the residue seems reasonable if we consider that the components corresponding to 68 dB are removed from the 70 dB level to form a continuous stream. Let us step back and consider some of the changes occurring when the level of a 1000 Hz tone is increased: a) the rate of firing of neural fibers responding to the fainter level increases; b) less sensitive fibers with a characteristic (best) frequency of 1000 Hz are brought into play; c) a spread of excitation occurs, with fibers having characteristic frequencies differing from 1000 Hz responding (however, with phase-locking to the frequency of the 1000 Hz tone). Thus, when the louder 1000 Hz tone is an inducer, it follows that the residue remaining after subtracting components corresponding to a 68 dB level no longer corresponds to that occurring normally with a 1000 Hz tone. We are at this point unable to speculate further without additional observations.

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1. Chalikia, M.H., & Warren, R.M. The role of spectral factors in phonemic transformation.
2. Warren, R.M., & Bashford, J.A., Jr. Type I and Type II perception: When acoustic sequences are not perceptual sequences.

#### PROFESSIONAL PERSONNEL

In addition to the Principal Investigator, R.M. Warren, Ph.D., James A. Bashford, Jr., Ph.D. has participated in the project as Associate Researcher. Graduate students who have been assisting in this project were Bradley S. Brubaker, Eric Healy, Keri. R. Riener, Christine M. VanRyzin, and Daniel G. Zuck.

#### PROFESSIONAL INTERACTIONS OF PRINCIPAL INVESTIGATOR

- A. Papers presented at National Meetings of the Acoustical Society of America. During Grant Period (1 September, 1988 - 30 September, 1991) [See Appendices for full texts].
  1. "Discrimination of recycled word-length sequences." Journal of the Acoustical Society of America, 1988, 84, S141 (Abstract).
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  5. "Mapping the organization of vowel sequences into words." Journal of the Acoustical Society of America, 1990, 87, S160 (Abstract).

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  8. "Verbal organization of vowel sequences: Effects of repetition rate and stimulus complexity." Journal of the Acoustical Society of America, 1990, 88, S55 (Abstract).
  9. "The pitch of odd-harmonic tones: Evidence of temporal analysis in the dominance region." Journal of the Acoustical Society of America, 1990, 88, S48 (Abstract).
- B. Invited paper presented at the First International Conference on Music Perception and Cognition, Kyoto, Japan, October, 1989, "Melodic and nonmelodic pitch patterns: Effects of duration on perception," (also served as session chairman). Paper published in the Conference Proceedings, pp. 343-348. [See Appendix for text]
- C. Participant at Osaka Symposium on Perception, sponsored by the Department of Psychology, University of Osaka, Japan, October 1989.
- D. Visiting Senior Scientist at the Basic Research Laboratories of Nippon Telegraph and Telephone Company at Musashino, Tokyo during May and June, 1990. He presented a series of lectures dealing with his research, served as consultant for ongoing research programs, and initiated two experimental studies: One dealt with perceptual organization of sequences of steady-state Japanese vowels (conducted with Shigeaki Amano); the other dealt with dichotic verbal transformations involving both English and Japanese words (conducted with Makio Kashino). Papers based upon these studies were presented by Kashino-san and Amano-san at a meeting of the Acoustical Society of Japan, September, 1990.
- E. The Principal Investigator was a Presenter at a Tutorial Workshop entitled "Cognitive Aspects of Human Audition" (organized by the Hearing Group of the French Acoustical Society and IRCAM at Paris), 21-22 February 1991. His contribution on "Perception of Global Properties of Sounds Sequences" will be published as a chapter in a book to appear in both English and French version (English title "Cognitive Aspects of Human Audition", S. McAdams & E. Bigand, Eds. Oxford University Press).

#### APPENDICES

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2. Warren, R.M. & Bashford, J.A. Jr. Broadband repetition pitch: Spectral dominance or pitch averaging? Journal of the Acoustical Society of America, 1988, 84, 2058-2062.
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9. Warren, R.M., Gardner, D.A., Brubaker, B.S., & Bashford, J.A., Jr. Melodic and nonmelodic sequences of tones: Effects of duration on perception. Music Perception, 1991, 8, 277-290.
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11. Chalikia, M.H., & Warren, R.M. Phonemic transformations: Mapping the illusory organization of steady-state vowel sequences. Language and Speech, (in press).
12. Bashford, J.A., Jr., Riener, K.R., & Warren, R.M. Increasing the intelligibility of speech through multiple phonemic restorations. Perception & Psychophysics, (in press).
13. Warren, R.M. Perception of acoustic sequences: Global integration versus temporal resolution. In S. McAdams & E. Bigand (Eds.), Cognitive Aspects of Human Audition. Oxford: Oxford University Press [French edition to be published by INSERM in their Editions Internationales Médicales] (in press).
14. Chalikia, M.H., & Warren, R.M. The role of spectral factors in phonemic transformation (submitted for publication).
15. Warren, R.M., & Bashford, J.A., Jr. Type I and Type II perception: When acoustic sequences are not perceptual sequences (submitted for publication).
16. Text of Poster "Discrimination of recycled word-length sequences." Presented at the November, 1988 Meeting of the Acoustical Society of America.
17. Text of Poster "Learning to identify phonemic orders." Presented at the November, 1988 Meeting of the Acoustical Society of America.

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18. Text of Poster "Pattern recognition within spectrally isolated regions of broadband sounds." Presented at the May, 1990 Meeting of the Acoustical Society of America.
19. Text of Poster "Auditory memory for long-period random waveforms." Presented at the May, 1990 Meeting of the Acoustical Society of America.
20. Text of Paper "Mapping the organization of vowel sequences into words." Presented at the May, 1990 Meeting of the Acoustical Society of America.
21. Text of Paper "Increasing the intelligibility of speech through multiple phonemic restorations." Presented at the May, 1990 Meeting of the Acoustical Society of America.
22. Text of Paper "Spectral factors in the organization of vowel sequences into words." Presented at the November, 1990 Meeting of the Acoustical Society of America.
23. Text of Paper "Verbal organization of vowel sequences: Effects of repetition rate and stimulus complexity." Presented at the November, 1990 Meeting of the Acoustical Society of America.
24. Text of Paper "The pitch of odd-harmonic tones: Evidence of temporal analysis in the dominance region." Presented at the November, 1990 Meeting of the Acoustical Society of America.